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November 14, 1980

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Principal Investigator:

M. Griggs
Science Applications, Inc.
P. O. Box 2351
La Jolla, California 92037

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Ground truth measurements of the atmospheric aerosol optical thickness and radiance data for the GOES-1 and SMS-2 satellites, show that the satellite sensors were stable over a period of eighteen months, and that there is probably a difference in the radiometric calibrations of the sensors. Theoretical calculations show that errors, due to variations in the aerosol properties, in inferring the aerosol content from a satellite radiance measurement are similar for the nadir viewing sensors (e.g., Landsat MSS) and for the scanning sensors (e.g., NOAA-6 AVHRR).

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ABSTRACT

Ground truth measurements of the atmospheric aerosol optical thickness and radiance data for the GOES-1 and SMS-2 satellites, show that the satellite sensors were stable over a period of eighteen months, and that there is probably a difference in the radiometric calibrations of the sensors. Theoretical calculations show that errors, due to variations in the aerosol properties, in inferring the aerosol content from a satellite radiance measurement are similar for the nadir viewing sensors (e.g., Landsat MSS) and for the scanning sensors (e.g., NOAA-6 AVHRR).

ACKNOWLEDGEMENT

The author would like to thank Dr. L. Ruhnke for providing sun-photometer data, and for his encouragement in this investigation.

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1. INTRODUCTION

The investigation of the satellite technique[1] to measure tropospheric aerosols has continued both experimentally and theoretically. Additional ground truth measurements and satellite measurements have been obtained for the GOES-1 and SMS-2 satellites, and compared with earlier results. A discussion of the relative sensitivities of the different satellite sensors for monitoring aerosol changes is given. The results of calculations to investigate the errors in the technique due to variations in the refractive index, the size distribution, and the vertical distribution of the aerosols are discussed.

2. GROUND TRUTH MEASUREMENTS

The acquisition of ground truth measurements of the aerosol optical thickness at the time of satellite overpasses has continued when possible during other Navy programs. Measurements have been made by NRL personnel at San Nicolas Island, California; at Panama City, Florida; at Wallops Island, Virginia; in the North Sea (Marsen experiment); and on the USNS Hayes off the Virginia coast; in addition, measurements have been made by SAI at San Diego.

In order to obtain reliable measurements of aerosol optical thickness it is important to have a stable well-calibrated instrument. A recent analysis[(2)] of seven NOAA photometers showed that over a period of about one year the instrument calibration constant changed by as much as 16.5%, and that much of the change is probably due to accumulation of dirt on the filters. The analysis suggested that if the instruments are kept in a clean dust-free environment then the uncertainty in the instrument calibrations could be kept within acceptable limits of a few percent.

In light of the findings for these NOAA sunphotometers (manufactured by Eppley Laboratories under NOAA specifications) it was decided to investigate the stability of the Volz sunphotometers used by NRL in this program. A check on the stability of a sunphotometer is best accomplished by periodically making careful Langley plots, or by periodically comparing it with a reference sunphotometer which is regularly calibrated. In the absence of such checks, the use of two sunphotometers, as done by NRL, can be very useful. If a measurement is repeated with the second sunphotometer immediately after making one with the first sunphotometer, a plot of the readings can be made, as shown in Fig. 1 for the NRL sunphotometers No. 448 and No. 457. This plot shows that in the period June 1979 to April 1980, the response of the 500 nm channels have not changed with respect to each other, indicating that the calibration constants are probably unchanged in that period of time (it is possible, but unlikely that each has changed by the same percentage). A similar plot for the 440 nm channels is given in Fig. 2, and for these channels, a change in one of the instruments may have occurred between June 1979 and April 1980, although

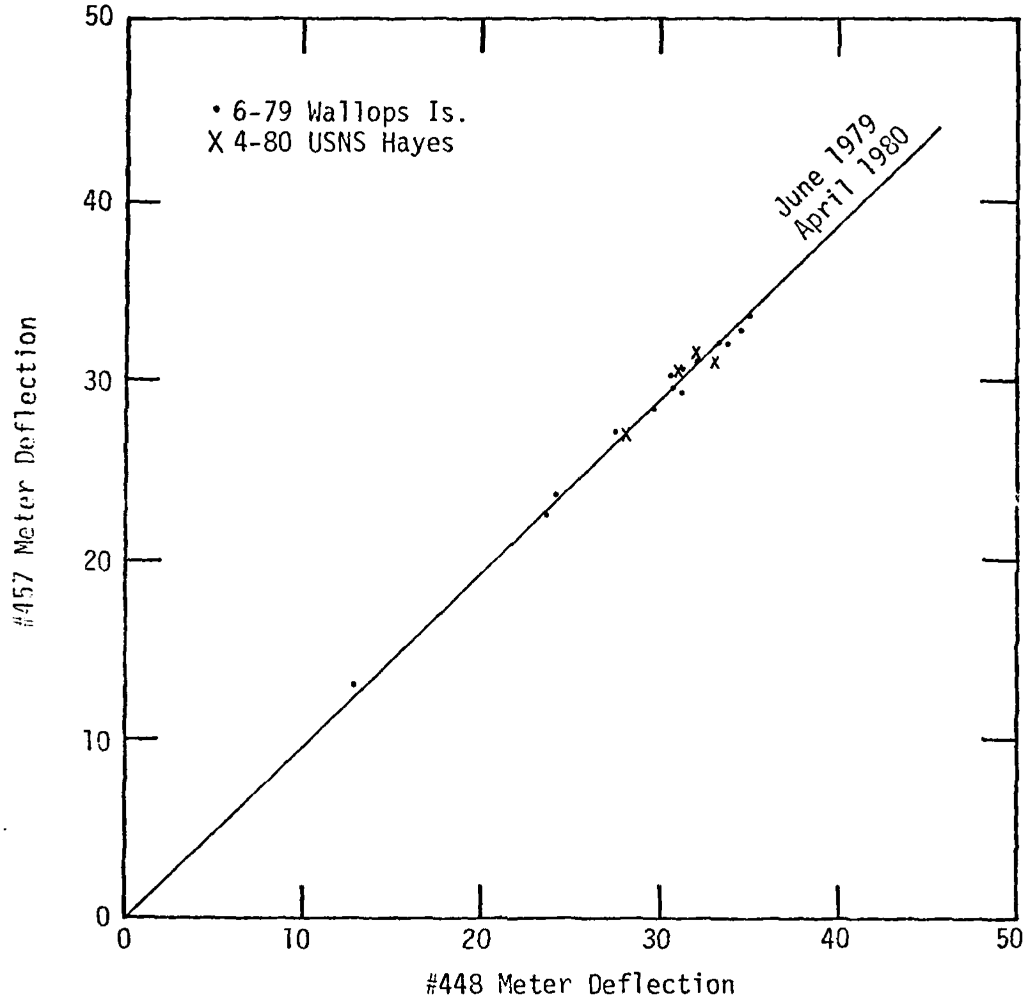

Figure 1. Comparison of NRL Sunphotometers (500 nm).

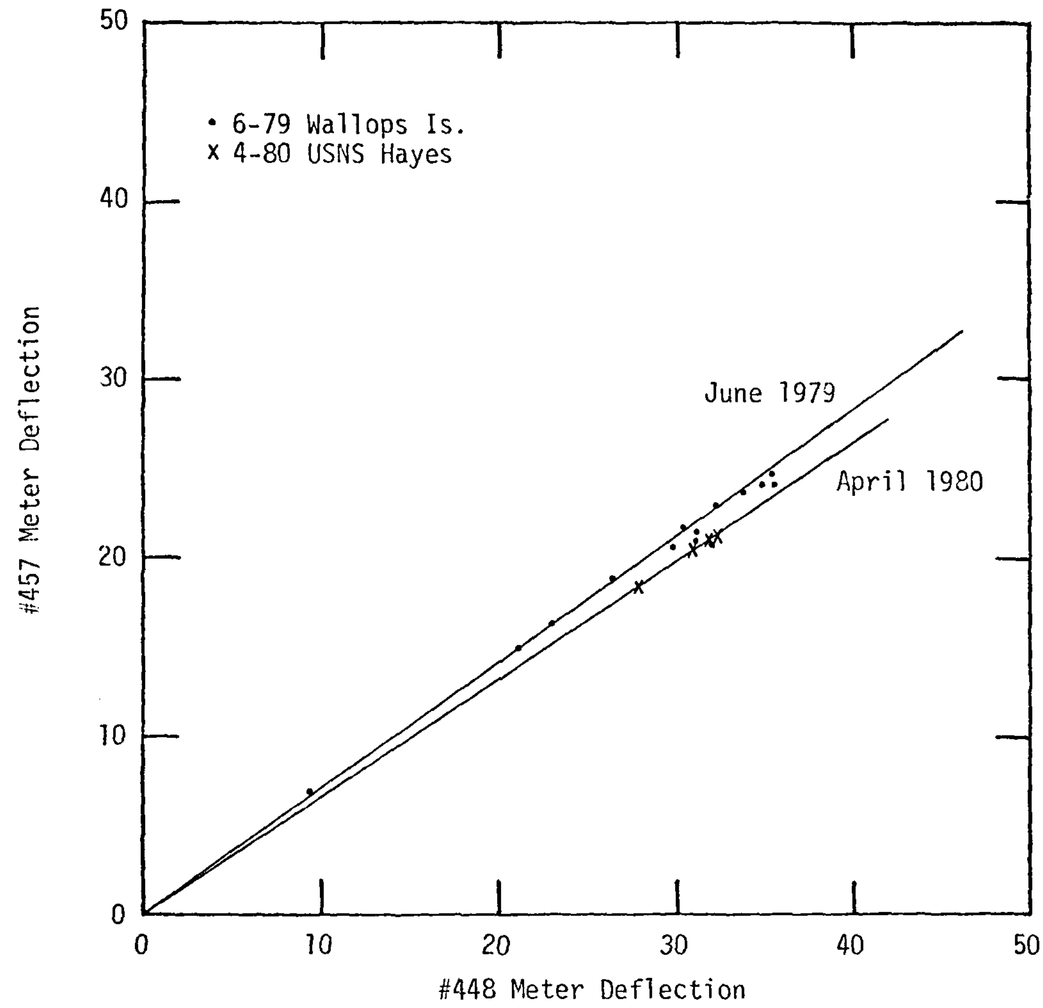

Figure 2. Comparison of NRL Sunphotometer (440 nm).

three of the earlier points are so close to the later points, a change is not obvious. Thus, in analyzing the measurements, we will assume that no significant change in the calibration constants has occurred in this time period.

Further evidence of the stability of these sunphotometers is provided by data taken at Wallops Island on 25 June 1979, when a few measurements were obtained over a range of air masses sufficient to make rough Langley plots for each instrument, as shown in Fig. 3. These data are too few, (and the atmospheric optical thickness does not seem constant over the whole data-taking period) to make a reliable calibration. However, the calibration constants (I_o) (see Table 1) which would be inferred from the intercepts on the ordinate are very close to those originally given with instruments, except for the 500 nm channel of No. 448. Thus, except for this channel, we assume that the original I_o values are still valid through April 1980. For the 500 nm channel of No. 448 we assume I_o = 51.5 (determined from Fig. 1, assuming I_o = 50.0 for No. 457). All the data taken in 1979 and 1980 indicate that the I_o for No. 448 is larger than that for No. 457, in contrast to the original values, suggesting either an incorrect original value for No. 448, or a change since it was obtained.

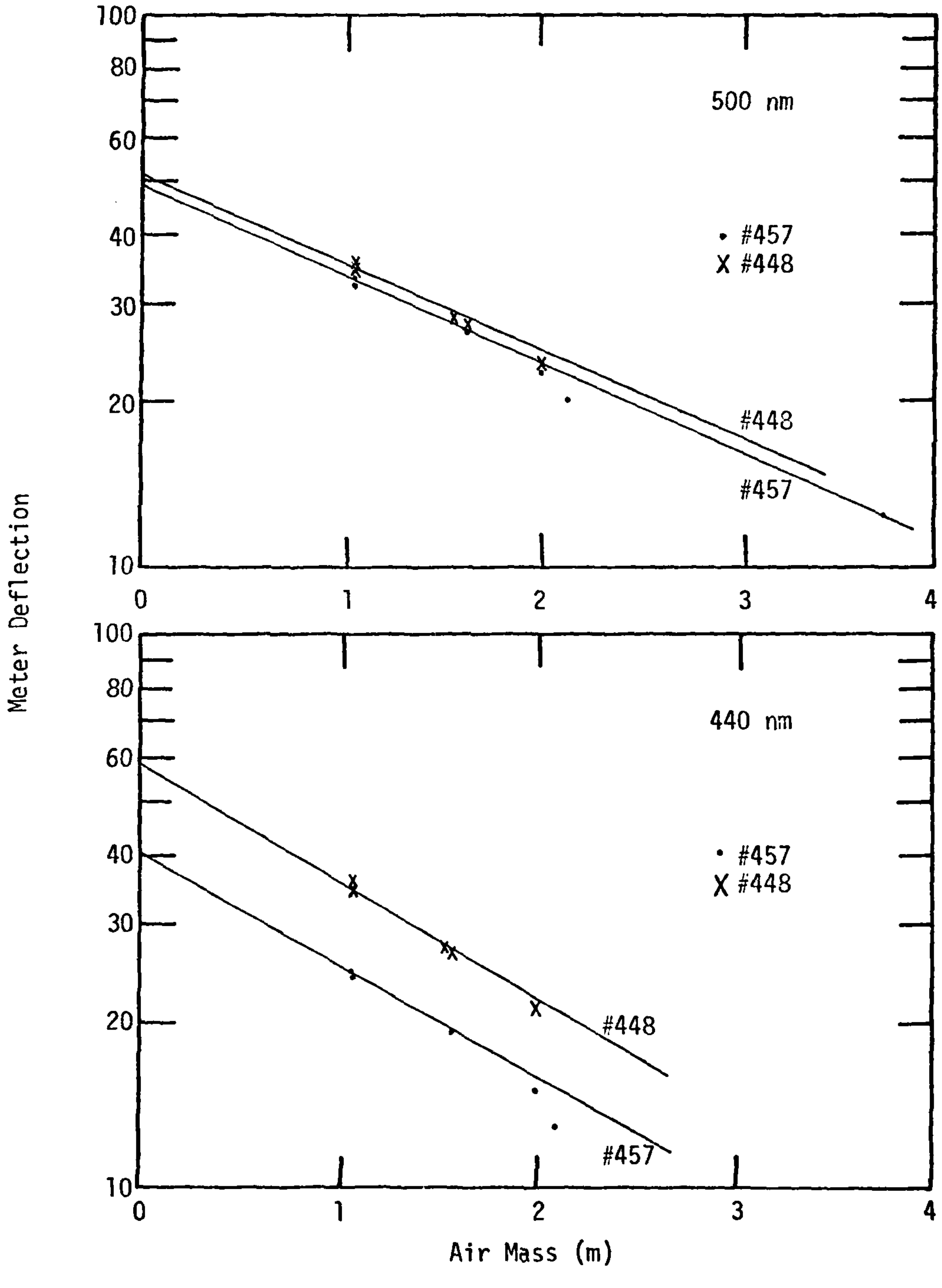

Figure 3. Langley Plots for NRL Sunphotometers.

Table 1. Sunphotometer Calibration Constants

	500 nm		440 nm	
	Given (1978)	Measured (1979)	Given (1978)	Measured (1979)
No. 448	47.8	51.1	57.5	58.4
No. 457	50.0	49.6	39.5	40.8

3. SATELLITE MEASUREMENTS

The original GOES-1 results[2] obtained during the 1977 EOMET cruise across the North Atlantic have been supplemented by two more data points obtained just off the coast from Panama City, Florida in December 1978. The results given in Fig. 4 show very good agreement with the Atlantic data obtained nineteen months earlier, suggesting that the sensitivity of the GOES-1 sensor is quite stable over long periods.

Data for the SMS-2, the same type of satellite as GOES-1, but positioned over the Pacific Ocean, were obtained for five days at San Nicholas Island in May 1978, and for five days at San Diego in November 1979. At San Nicolas Island, the aerosol content was effectively the same each day, and the SMS-2 measured effectively the same radiance each time, thus verifying the repeatability of the technique. The data for San Diego are also given in Fig. 4 and show that the slope of the radiance vs aerosol content relationship for SMS-2 is the same as that found for GOES during the EOMET cruise. The difference between the two lines could be due to a difference in the aerosol properties between the Atlantic and Pacific Oceans, but, as discussed previously,[1] it is most likely due to a difference in the radiometric calibrations of the satellite sensors.

It is noted in Fig. 4 that one of the San Diego data points is significantly higher than expected. However, if the sensor digital count at this time had been just one count less, then the radiance would be 1.07 rather than 1.42 $mW/cm^2/\mu m/Sr$, bringing it almost to the expected value. This large change in radiance for a change of one digital count, which is certainly a possible error in the GOES/SMS system, clearly illustrates the insensitivity of this sensor, as discussed in Section 4.

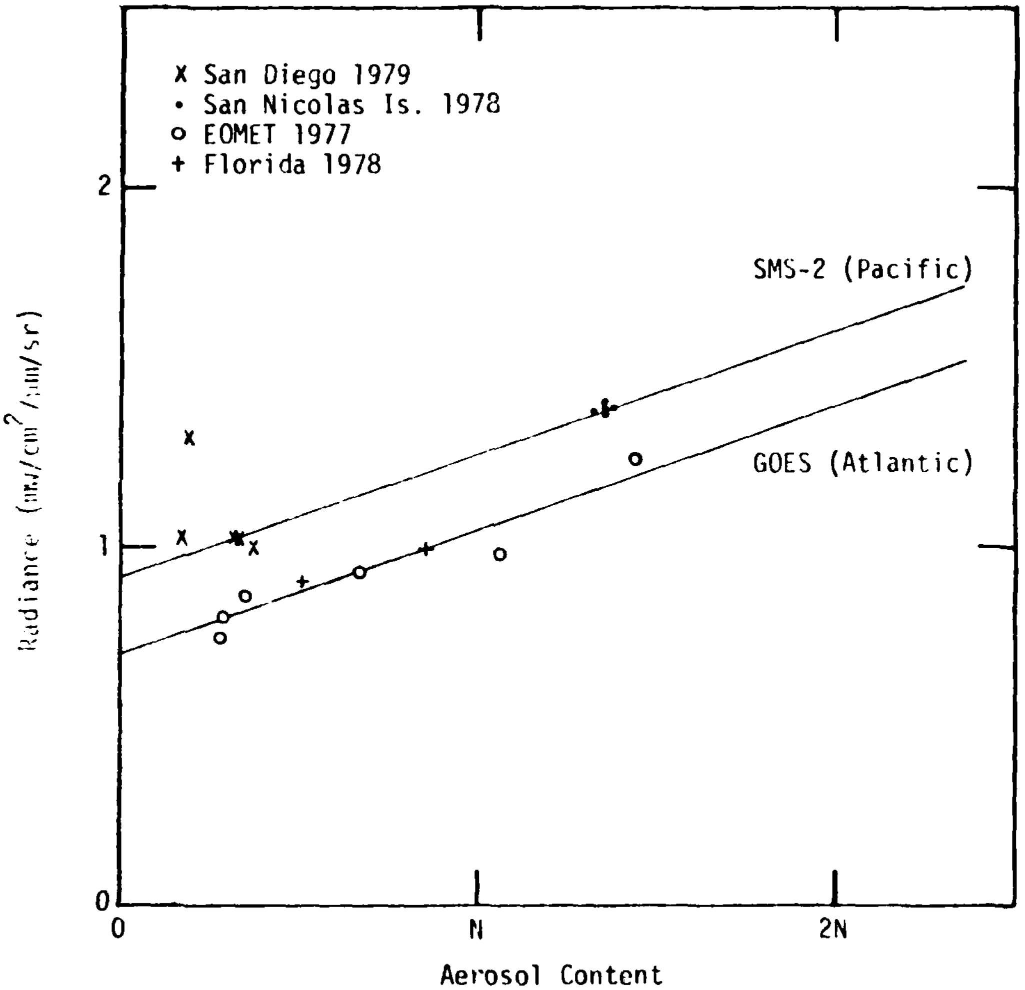

Figure 4. Satellite Radiance Versus Aerosol Content.

4. COMPARISON OF SATELLITE SENSORS

The relationship between upwelling radiance and the atmospheric aerosol content was originally demonstrated using Landsat data.[3] Since then, this study has found similar relationships for sensors on NOAA-5, GOES-1 and SMS-2.[1] However, the sensitivities of the systems are quite different. NOAA-5, which is no longer operating, was not suitable for aerosol monitoring due to a non-random noise problem, and the GOES/SMS sensors are only 6-bit systems and do not provide useful radiance sensitivity for monitoring small aerosol content changes. The most useful satellites currently in orbit are NOAA-6 (10-bit AVHRR), and NIMBUS 7 which has the 8-bit CZCS, designed specifically for measuring the small radiances over oceans. Unfortunately digital data for the CZCS are not routinely recorded, and are not readily available, whereas the NOAA-6 (to be replaced by NOAA-7 in late 1980) data have been routinely archived by NOAA since early 1980. Thus the NOAA-6 AVHRR is the most useful operational satellite for accurately monitoring atmospheric aerosols on a routine basis.

5. INFLUENCE OF AEROSOL PROPERTIES ON THE RADIANCE-AEROSOL CONTENT RELATIONSHIP

Theoretical calculations with the Dave[4] atmospheric scattering code have been used to determine the effect of aerosol properties on the radiance-aerosol content relationship. These properties include the aerosol size distribution, real and imaginary refractive indices, and the vertical distribution of the aerosols. The calculations have been made, assuming that the aerosol size distribution is represented by the Junge distribution:

$$dn(r) = Cr^{-\nu} \, d \log r$$

where $n(r)$ is the number of particles with radius r, C is a constant depending on the number of particles per unit volume, and ν ranges between 2.5 and 4 for typical size distributions.

5.1 LANDSAT DATA

Calculations of the effect of ν on the radiance-aerosol content relationship have been made for each of the Landsat MSS wavelengths for the standard[5] Landsat viewing conditions of a nadir look angle and a sun zenith angle of 63°. The results (for a refractive index of 1.5), given in Figure 5, show that the influence of ν varies with wavelength and has a minimum effect near 0.8 μm. Thus, the use of a satellite sensor at this wavelength should give the best estimate of the aerosol content. It was found in the Landsat study[5] that indeed the MSS 6 (0.75 μm) showed the best radiance-aerosol content relationship with the least scatter of data points. The spectral variation of the influence of ν on the radiance also suggests that spectral measurements of the upwelling radiance could provide information on the size distribution; wavelengths greater than about 0.6 μm would be preferred for such an analysis in order to minimize subsurface effects. The CZCS is preferred to the MSS for this analysis since it can measure the ocean radiances more accurately, and thus more readily detect the small radiance changes due to changes in the size distribution.

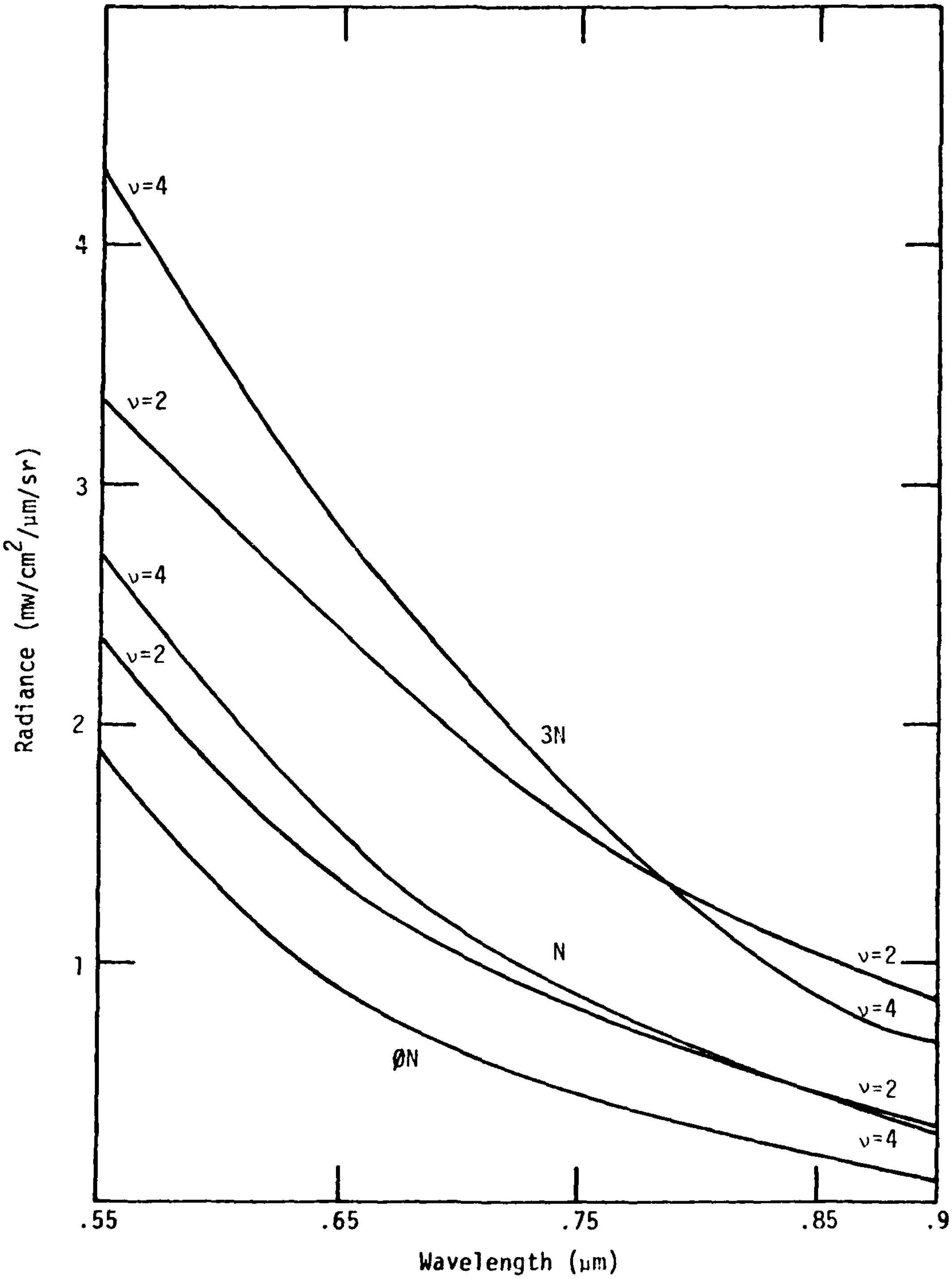

Figure 5. Theoretical Radiance Versus Wavelength as Function of Aerosol Content and Size Distribution (Nadir-viewing with Sun Zenith Angle of 63°).

It was shown previously[5] for the standard Landsat viewing conditions that increasing the real part of the refractive index increases the upwelling radiance for a given aerosol content, and that increasing the imaginary component reduces the radiance. In addition it was found that the vertical distribution of the aerosols did not significantly influence the radiance.

5.2 OTHER SATELLITE DATA

The effects of the aerosol properties described above were determined for Landsat MSS observations in the nadir. However, for the other satellites discussed in Section 3 and 4, the sensors scan across the orbital path and experience a variety of sun angles. Thus the viewing and sun angles differ significantly from those for the Landsat observations, resulting in different scattering angles; hence the aerosol properties may cause different effects. To investigate this possibility a computer code developed by us for NOAA[6] to analyze NOAA-6 data has been utilized.

The NOAA-6 code enables the aerosol content (0-10N) to be determined from a radiance measurement by the AVHRR 0.65 μm channel, given the viewing angle and the sun angle. The code is based on radiance calculations with the Dave code using an aerosol model which best fit the Landsat MSS 6 (0.65 μm) data at San Diego, viz. refractive index, $n = 1.5$, $\nu = 3.5$, and an ocean albedo of 0.015. The code considers a range of sun zenith angles ($\theta_0 = 42 - 84°$), sun azimuth angles ($\phi = 140 - 180°$), and viewing angles ($\theta = 0 - 84°$) to cover all conditions to be found in the NOAA-6 orbit when scanning away from the sun; these values may not cover all situations for other satellites. For this investigation the calculations have been repeated for three different sets of aerosol properties:

Set 1. $n = 1.33$, $\nu = 3.5$
Set 2. $n = 1.50-0.01i$, $\nu = 3.5$
Set 3. $n = 1.50$, $\nu = 2.5$

and compared with the standard set of radiance values in the NOAA-6 code, to obtain a tabulation of the percentage radiance difference, as a function of sun

angles, viewing angle and aerosol content, for each set of aerosol properties. The values of n represent the extreme values which are typically found in the atmosphere. The values of ν were chosen to determine the effect of a change of 1.0 in ν; the previous Landsat study[5] showed that the radiance change at a given aerosol content is approximately proportional to the change in ν, in the nadir viewing case. Selected results of the comparisons were given in Table 1, showing the percentage difference in radiance from the Landsat model computed for each set of aerosol properties given above.

It is found for Set 1 that the change to the lower refractive index produces a radiance change always within about ±1-3% of the percentage change observed at the Landsat conditions ($\theta_0 = 63°$, $\theta = 0°$) for a given aerosol content. The difference increases with N up to 6N and then is approximately constant up to 10N. The percentage changes are not very dependent on the angles θ_0, θ, and ϕ, except for large sun and viewing angles (>72°) where the changes actually decrease.

For Set 2 it is found that the introduction of some absorption by the aerosol produces changes up to two times larger than found in Set 1, and which increase as N increases. The changes are generally about 1-3% less than the percentage change observed for the Landsat conditions, and again are approximately independent of angle up to larger values of θ_0 or θ (>72°) where the changes are smaller.

For Set 3, the reduction of ν produces a more dramatic effect on the radiance change in terms of its dependence on angle. The magnitude of the change is generally less than in Sets 2 and 3, but can be positive or negative, depending mainly on the angles θ and ϕ, with a lesser dependence on θ_0. The difference increases with N up to about 4N, and then decreases up to 10N. The magnitude of the error is about the same as for the Landsat conditions, but may be positive or negative.

It appears from the above results that the effects of variations in the aerosol properties, are not significantly different for a scanning sensor than for the Landsat MSS, except for variations in the size parameter ν which can produce radiance changes in the scanning sensor with the opposite sign of those for the Landsat MSS, but still of about the same magnitude.

These radiance changes have been translated into errors in determining the aerosol content from the NOAA-6 code when the aerosol properties are different from the Landsat model. These errors are shown in Table 2 for the radiance changes given in Table 1. It is noted that the same radiance change can produce different errors in aerosol content for different sun and viewing angles, since the slope of the radiance-aerosol content relationship is angle dependent.

Similar calculations of radiance change and aerosol content error were made for a change in the vertical distribution. A layer of aerosols with a number density seventy five times greater than normal was inserted at an altitude of 5 km. The calculations showed that even with this extreme variation, which perhaps could be found in a Saharan dust outflow over the Atlantic, the scanning sensor would experience about the same radiance change (~+5%) as the Landsat MSS; the corresponding error in aerosol content is approximately +10%.

Table 2. Percentage Change in Radiance for Changes in Aerosol Properties (Aerosol Content = 1N)

		θ_o = 66°			θ_o = 42°		
	$\theta \backslash \phi$	140°	160°	180°	140°	160°	180°
n=1.33 ν=3.5	0.00	-11.	-11.	-11.	-8.	-8.	-8.
	6.00	-10.	-10.	-10.	-8.	-8.	-8.
	12.00	-10.	-9.	-9.	-8.	-9.	-9.
	18.00	-9.	-9.	-9.	-9.	-11.	-10.
	24.00	-9.	-9.	-8.	-9.	-11.	-11.
	30.00	-9.	-8.	-8.	-10.	-11.	-11.
	36.00	-9.	-9.	-9.	-10.	-11.	-15.
	42.00	-9.	-9.	-10.	-10.	-12.	-16.
	48.00	-9.	-10.	-11.	-10.	-12.	-15.
	54.00	-9.	-11.	-11.	-9.	-12.	-12.
	60.00	-8.	-11.	-14.	-9.	-11.	-12.
	66.00	-8.	-11.	-15.	-8.	-9.	-10.
	72.00	-7.	-10.	-13.	-8.	-8.	-9.
	78.00	-6.	-8.	-9.	-8.	-7.	-7.
	84.00	-5.	-6.	-7.	-7.	-6.	-6.
n=1.5 -0.01i ν=3.5	0.00	-14.	-14.	-14.	-11.	-11.	-11.
	6.00	-13.	-13.	-13.	-11.	-11.	-11.
	12.00	-13.	-13.	-13.	-11.	-11.	-12.
	18.00	-13.	-12.	-12.	-12.	-12.	-12.
	24.00	-13.	-12.	-12.	-12.	-13.	-14.
	30.00	-13.	-13.	-13.	-13.	-14.	-16.
	36.00	-13.	-13.	-13.	-13.	-14.	-15.
	42.00	-13.	-14.	-14.	-13.	-15.	-17.
	48.00	-13.	-14.	-15.	-13.	-15.	-16.
	54.00	-14.	-15.	-16.	-13.	-15.	-15.
	60.00	-14.	-16.	-17.	-13.	-14.	-15.
	66.00	-14.	-16.	-18.	-13.	-14.	-12.
	72.00	-14.	-15.	-16.	-13.	-13.	-13.
	78.00	-12.	-13.	-14.	-12.	-12.	-12.
	84.00	-9.	-10.	-10.	-9.	-9.	-9.
n=1.5 ν=2.5	0.00	-9.	-9.	-9.	-7.	-7.	-7.
	6.00	-10.	-9.	-9.	-6.	-6.	-6.
	12.00	-8.	-10.	-9.	-4.	-3.	-4.
	18.00	-8.	-9.	-9.	-4.	-1.	2.
	24.00	-9.	-7.	-8.	-0.	7.	9.
	30.00	-8.	-6.	-6.	-1.	9.	9.
	36.00	-8.	-4.	-3.	-0.	8.	13.
	42.00	-6.	-2.	2.	-1.	7.	8.
	48.00	-6.	2.	9.	-2.	11.	13.
	54.00	-6.	7.	9.	-4.	7.	9.
	60.00	-6.	8.	14.	-6.	2.	9.
	66.00	-5.	10.	9.	-6.	-2.	2.
	72.00	-4.	8.	14.	-6.	-3.	-3.
	78.00	-3.	6.	10.	-7.	-4.	-5.
	84.00	-3.	3.	10.	-5.	-4.	-6.

Table 3. Percentage Errors in Aerosol Content
(Produced by Radiance Changes in Table 1)
for Changes in Aerosol Properties (Aerosol Content = 1N)

		$\theta_0 = 66°$			$\theta_0 = 42°$		
	$\theta \backslash \phi$	140°	160°	180°	140°	160°	180°
	0.00	-25.	-25.	-25.	-24.	-24.	-24.
	6.00	-25.	-25.	-25.	-24.	-24.	-24.
	12.00	-25.	-24.	-24.	-25.	-25.	-26.
	18.00	-24.	-23.	-23.	-26.	-28.	-29.
	21.00	-23.	-23.	-22.	-27.	-30.	-31.
n=1.33	30.00	-23.	-22.	-23.	-28.	-31.	-31.
ν=3.5	36.00	-22.	-23.	-24.	-28.	-31.	-38.
	42.00	-22.	-24.	-27.	-27.	-30.	-39.
	48.00	-21.	-26.	-29.	-26.	-30.	-37.
	54.00	-21.	-27.	-28.	-24.	-30.	-30.
	60.00	-21.	-27.	-34.	-23.	-27.	-30.
	66.00	-20.	-27.	-35.	-22.	-24.	-27.
	72.00	-19.	-26.	-33.	-21.	-22.	-23.
	78.00	-19.	-26.	-28.	-23.	-22.	-22.
	84.00	-25.	-32.	-38.	-31.	-29.	-29.
	0.00	-32.	-32.	-32.	-33.	-33.	-33.
	6.00	-32.	-32.	-32.	-33.	-33.	-33.
	12.00	-32.	-32.	-32.	-34.	-34.	-34.
	18.00	-32.	-32.	-32.	-34.	-35.	-36.
	24.00	-32.	-33.	-33.	-35.	-37.	-38.
n=1.5	30.00	-33.	-33.	-33.	-35.	-38.	-39.
-0.01i	36.00	-33.	-34.	-34.	-35.	-38.	-40.
ν=3.5	42.00	-33.	-35.	-36.	-35.	-38.	-42.
	48.00	-33.	-36.	-38.	-34.	-38.	-40.
	54.00	-34.	-37.	-39.	-34.	-38.	-38.
	60.00	-34.	-38.	-40.	-33.	-36.	-38.
	66.00	-34.	-39.	-43.	-33.	-35.	-36.
	72.00	-35.	-39.	-42.	-33.	-34.	-35.
	78.00	-36.	-41.	-44.	-34.	-35.	-36.
	84.00	-45.	-51.	-57.	-41.	-42.	-43.
	0.00	-21.	-21.	-21.	-21.	-21.	-21.
	6.00	-25.	-23.	-22.	-17.	-19.	-19.
	12.00	-20.	-25.	-23.	-11.	-10.	-11.
	18.00	-20.	-23.	-23.	-10.	-2.	5.
	24.00	-23.	-18.	-21.	-1.	19.	25.
n=1.5	30.00	-19.	-17.	-17.	-2.	25.	24.
ν=2.5	36.00	-21.	-10.	-9.	-1.	22.	34.
	42.00	-15.	-5.	6.	-3.	20.	19.
	48.00	-15.	5.	25.	-5.	27.	33.
	54.00	-15.	16.	24.	-11.	19.	23.
	60.00	-15.	22.	36.	-15.	6.	24.
	66.00	-14.	25.	24.	-15.	-5.	6.
	72.00	-11.	22.	42.	-17.	-8.	-8.
	78.00	-10.	21.	38.	-21.	-13.	-15.
	84.00	-16.	18.	67.	-23.	-19.	-21.

6. CONCLUSIONS

The calculations show that errors, due to variations in the aerosol properties, in inferring the aerosol content from a satellite radiance measurement are similar for nadir viewing sensors, such as the Landsat MSS, and for scanning sensors, such as the NOAA-6 AVHRR. In comparing the calculated radiance changes, due to changes in the aerosol properties, with the scatter of data in the measured radiance-aerosol content relationships found for the different satellites,[1] it appears that variations in the aerosol properties must be relatively small over the oceans.

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